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RESEARCH NOTE
ERL-0828-RN

PRELIMINARY INVESTIGATION OF AN INTEGRATED OPTIC SAMPLER FOR HF SIGNALS (U)

by

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ELECTRONICS RESEARCH LABORATORY

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SUMMARY

A compact, rugged and inexpensive optical sampling system has been constructed. The aperture time of the sampler is estimated to be 75 ps, and sampling rates of 100 MHz and 250 MHz have been demonstrated. The performance of the demonstrator can be enhanced to gigahertz sampling rates without a substantial increase in cost.

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FIGURES

1 INTRODUCTION

In this report a compact, inexpensive electro-optic sampling demonstrator suitable for use at HF communications frequencies is described. In previous work [1], electro-optic sampling of a microwave signal that is phase-locked to the repetition frequency of an ultrafast pulsed laser was demonstrated. The system had good sensitivity and dynamic range with a theoretical bandwidth in excess of 300 GHz (in practice the system would actually be limited by the launching technology required to get the signal onto and off the electro-optic sampling structure).

When the rf signal is phase-locked to the laser repetition rate, the signal at each point in time is sampled over many millions of acquisitions, and then the delay between the optical trigger pulse and the optical sampling pulse is stepped to begin the measurement of the next data point. In this respect the "repetitive sampling" configuration operates in a similar manner to a digital sampling oscilloscope used in the averaging mode.

The requirement that the rf signal be phase-locked to the laser generally constrains the utility of the technique to laboratory-type device characterisation and calibration measurements. It is clear that for real-time acquisition of non-repetitive signals (such as HF communications signals) or for the sampling of repetitive signals (such as radar pulses) for which it may not be possible to phase-lock the repetition rate of the laser to the signal, the architecture described above is of no use.

The aim of this investigation has been to develop a rugged and inexpensive optical sampling system suitable for sampling HF signals. The output of such a system is a train of optical pulses the amplitude of which reflects the amplitude of the rf signal. These pulses can then be used as the basis for any number of different signal processing architectures. For example:

a. the pulses can be detected by a photodiode and processed by a normal A/D converter. Because the initial sampling process has been divorced from the "hold" process required by the electronic A/D and the sample is acquired in tens of picoseconds (the optical pulse duration), the possibility exists for improved performance from conventional A/D converters. This may arise due to the fact that the RF signal to be sampled is essentially stationary over the picosecond aperture time of the sampling pulse, rather than exhibiting a significant variation as it may when sampled using a much slower conventional A/D (ie. essentially have an ultrafast optical pre-sampler)

b. the usual advantages of being in the optical domain may be exploited. For example, the sampling process may occur many kilometres away from the point at which the final signal processing occurs if the output pulses are coupled into an optical fibre (typical optical attenuation is about 0.3 dB/km). Wide bandwidth, high gain amplification of the sampled signal can be achieved by exploiting optical amplifiers instead of rf amplifiers. The intrinsic security of optical fibre and EMI immunity may be significant advantages under certain circumstances.

c. the sampling rate is determined by the pulse repetition frequency, which can be as high as 350 GHz [2]. At more reasonable sampling frequencies (eg. less than 20 GHz), it is relatively easy to exploit optical techniques to de-multiplex the successive optical samples to an array of lower bandwidth A/D converters, thereby extending the effective bandwidth of current electronics technology [3].

d. the output pulse train can be digitised by totally new, hybrid or all-optical A/D converter architectures. One possibility is analysed in [4], where an all-optical 1-bit oversampling scheme is proposed which exploits new, optically bi-stable switches known as self-electro-optic effect devices (SEED's) to achieve the necessary quantization of the optical output. By oversampling the signal and providing a feedback path to modify the input appropriately, it is possible to produce a bit stream such that the local average of the signal over the bandwidth of interest results in an accurate representation of the original signal. For example, the bit stream (+1, +1, +1, -1, +1, +1, -1, +1, -1, -1, -1, -1) corresponds to the signal 3, 1, -1, -3 for an oversampling rate of 3. The accuracy of the quantization increases with oversampling, the simplest architectures giving 1.5 bits of accuracy for every doubling of the oversampling rate [4].

The important initial step in realising all of the above possibilities is the construction of the optical sampler. The results of a preliminary investigation into such a device is the subject of this report.

2 SYSTEM CONSIDERATIONS

The basic layout of the system is shown below in Figure 2.1. A pulsed laser source is coupled via an optical fibre into an integrated optical amplitude modulator. The amplitude of the optical pulses exiting the modulator will vary approximately linearly with the rf signal amplitude applied to the modulator, thereby producing a sampled, optical version of the rf input signal.

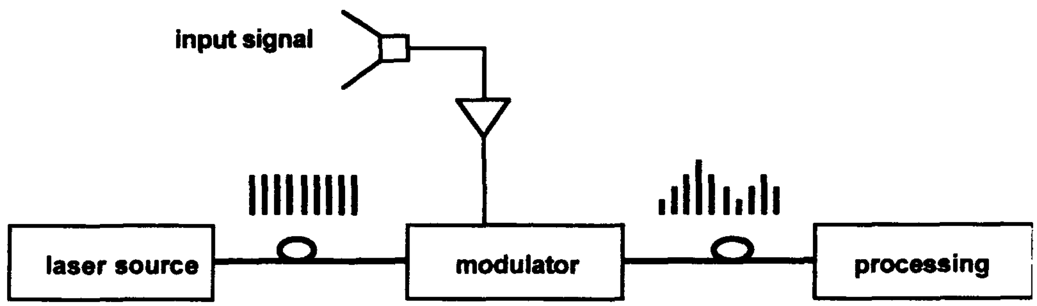

Figure 2.1 Electro-optic sampling

It was decided that a number of general system requirements were to be met:

a. the laser was to operate at one of the standard optical communications wavelengths (either 1.3 µm or 1.5 µm) - to ensure compatibility with standard telecommunications devices and systems,

b. the sampling frequency was to be at least 100 MHz - to demonstrate the ease with which bandwidths of interest for communications systems can be attained,

c. the aperture time of the sampling process (ie. the laser pulse duration) was to be of the order of tens of picoseconds - to maximise sampling accuracy and to ensure that the sampling rate was not limited by the physical overlap of successive sampling pulses,

d. the system was to be compact and inexpensive - to demonstrate that aperture times and sampling rates comparable to or well in excess of quite expensive electronics technology are readily achievable with optical technology, and that large unwieldy laser systems are not necessary to implement ultrafast optical sampling systems, and

e. the system was to consist entirely of "guided-wave" technologies (ie. integrated optics and fibre optics) - to ensure that the system was rugged and less susceptible to environmental conditions than optical systems that rely on "free space" propagation.

Points d and e were considered particularly important in order to demonstrate a system that was clearly capable of being packaged into a small size and removed from an optical bench and the controlled environment of an optical laboratory.

In the following section the general design goals of each of the system components is outlined. In Section 4 the results obtained from this preliminary investigation are presented, along with a discussion for extending the performance of the current system. Finally, in Section 5 the conclusions of this investigation are summarised.

3 COMPONENT DESIGN CONSIDERATIONS

In section two the overall characteristics required of the system were outlined. In this section the particular techniques and components chosen to fulfil these requirements are discussed.

3.1 The Optical Source

There are a number of factors which had to be considered when designing the optical source to be used for the experiment. Primarily, these were the type of laser, the operating wavelength and the technique which was to be used to produce the picosecond optical pulses. These questions are addressed in the following sections.

3.1.1 Type of Laser

The requirement that the system operate at standard telecommunications wavelengths along with the requirement that the system be compact limits the laser sources. For operation at 1.3 μm wavelength, the choices are semiconductor lasers or Nd:YAG lasers. For operation at a laser wavelength of 1.5 μm, semiconductor sources can be obtained commercially or optical-fibre lasers are available from research institutes such as the Optical Fibre Technology Centre at Sydney University (although during the preparation of this report the U.S. company United Technologies Optical Systems released preliminary specifications for their commercially available fibre laser system [5]). There are "exotic" laser sources such as optical parametric oscillators which are capable of providing 1.3 μm and 1.5 μm radiation however they are more complex, expensive and still mainly in the developmental stage, and as such are not serious contenders for use in the applications envisaged in this report.

Nd:YAG lasers have the advantages that they exhibit low relative intensity noise (RIN, typically -160 dBm/Hz), high output power (especially if diode-pumped rather than arc-lamp pumped), and high spectral purity (less of concern in pulsed applications). The disadvantages of Nd:YAG lasers are cost (especially if diode-pumped. A 10 mW CW laser costs about $25k [6]) and, in the case of arc-lamp pumping, relatively high maintenance costs and complexity.

In the future fibre lasers will probably be the ideal source for the application in mind. However, the diode pump lasers required for their operation are quite expensive and the lasers themselves are still more in the "research" category than the "established technology" category, although both of these problems are expected to improve very rapidly. Fibre lasers incorporating electro-optic modelocking have demonstrated 3.5 ps pulses at 20 GHz repetition rates [7] and 8 ps pulses at 30 GHz repetition rates [8]. Average output powers of several to over ten milliwatts are typical.

Semiconductor lasers at 1.3 μm and 1.5 μm have the advantages of relatively low cost (depending upon the type of laser), very high reliability, ready supply and long mean time to failure (MTTF, typically 450 000 hours). The disadvantages are lower optical powers, lower spectral purity and significantly higher RIN (typically ~ -120 to -140 dBm/Hz).

Given that the system is intended to be low cost and demonstrably rugged, it was decided that semiconductor lasers would be the optimal choice for the demonstrator system.

The choice between operating wavelengths was made based on the following observations: lasers operating at 1.5 μm have the advantage that commercially available erbium-doped fibre amplifiers can be used to boost the optical pulse power to that of diode pumped Nd:YAG lasers (and still be cheaper or of similar cost), however integrated optical modulators made for 1.5 μm exhibit a smaller rf to optical transduction efficiency than do modulators constructed for 1.3 μm operation, due to the larger widths of the optical waveguides required for 1.5 μm radiation. Since optical amplifiers were not going to be used in the demonstrator (again due to cost considerations), it was felt that the slightly better modulation efficiency of integrated optical modulators optimised for operation with 1.3 μm laser light was the deciding factor.

Based on the above considerations it was decided that a semiconductor laser with a wavelength of 1.3 μm would be the most suitable laser source.

The next question to answer was how to produce the picosecond optical pulses required for the experiment.

3.1.2 Optical Pulse Generation Techniques

There are two techniques which can be used to generate picosecond optical pulses at high repetition rates from semiconductor laser sources. These are known as *gain switching* and *mode-locking*.

Gain switching is by far the simplest technique to implement. As the name suggests, optical pulses are generated simply by applying a very fast electrical pulse to the laser which, once the current rises above the lasing threshold, produces a fast optical pulse.

The fast electrical pulse is usually generated by driving a step recovery diode (SRD) with a sinusoidal tone at the required sampling frequency. The output from the step recovery diode is a fast electrical pulse once every cycle, and it is this pulse which is used to drive the laser. Typically the electrical pulse widths are of the order of 120 ps, with pulse repetition rates up to 1 GHz commercially available as standard products [9]. Custom-made devices from standard suppliers are available for operation up to 3 GHz [9].

The technique of gain switching has the strengths that the implementation is simple, robust and inexpensive, with gain-switched lasers demonstrating quite good performance. When unpackaged laser chips are pulsed using this technique optical pulses of the order of 20-30 ps are routinely achieved [10]. Fairly straight-forward fibre pulse compression techniques have been used to reduce the pulse duration to 2-4 ps [10]. The rms pulse-to-pulse timing jitter of gain switched pulses is typically of the order of 1 ps [3, 10]. Optical pulse repetition rates of 2 GHz have been demonstrated [3].

The major disadvantages of the technique are that the optical pulse powers tend to be quite small (of the order of tens to hundreds of microwatts), and that the pulse *amplitude* jitter tends to be greater than that obtained from mode-locked semiconductor lasers. There is no significant difference between the timing jitter of typical gain switched and mode-locked semiconductor lasers (typically a factor of two or so). Both gain switched and mode-locked lasers exhibit timing jitter strongly correlated to the phase noise of the electrical drive circuits, with jitter less than 1 ps demonstrated. Gain switched lasers have an additional uncorrelated component which arises due to the random process of the onset of laser emission. Contributions of ~0.2 ps for correlated jitter and ~0.5 ps for uncorrelated jitter have been measured in gain switched laser diodes [11].

The technique of mode-locking essentially relies on impressing a periodic modulation (either phase or amplitude) onto the laser cavity modes such that the sidebands from any given mode overlap with the other longitudinal modes. This leads to a form of mutual injection locking, which results in a suppression of the usual random phase fluctuations between the various modes and hence a pulsed output. The mode-locking frequency is *critically* related to the round-trip time of photons in the laser cavity.

Mode-locking has the advantage that significantly higher pulse powers can be obtained than are achievable with gain switching (if the number of modes locked is N, then the peak pulse power is roughly N times the average power). Also, pulse durations from semiconductor lasers can be an order of magnitude smaller than those obtained from gain switching. Repetition rates can be as high as 350 GHz [2]. As a recent example of the types of lasers that are currently under development, researchers at Sandia National Laboratories have developed a passively mode-locked monolithic ring laser that produces 1.3 ps transform-limited optical pulses at a repetition rate of 86 GHz with 10 mW/pulse output power [12].

The technique of mode-locking has a number of significant disadvantages, however. These are mainly concerned with the complexity of the laser structures, the critical relationship between mode-locking frequency and cavity length, and the necessary cavity length required for mode-locking at frequencies at which useful *systems* can currently be implemented (ie. less than about 20 GHz).

The need to incorporate a "saturable absorber" structure (typically a stack of quantum wells) to achieve picosecond and sub-picosecond pulses means that these very special "extended cavity" lasers are not yet commercially available and are likely to be very expensive due to their complex structure. The critical relationship between cavity length and mode-locking frequency also means that these lasers are likely to be quite temperature sensitive (due to thermal expansion and contraction of the cavity), and hence the object of being able to remove the system from the laboratory environment could not be achieved without significant compensation circuitry (temperature stabilisation or direct stabilisation of the cavity length - probably electro-optically - in order to maintain the cavity length at the appropriate value to continue mode-locking under varying temperature conditions). The final consideration of *system* limitations arises through consideration of the maximum speed of *other* parts of the total system eg. high speed MMIC's, the switching speed of optically bistable devices, the speed of active optical devices for de-multiplexing the signal, etc.

Mode-locking at lower frequencies (less than ~20 GHz for typical length laser diodes) requires that one facet of the laser diode be anti-reflection coated, and an external mirror be used to form the laser cavity. These systems have very little chance of usefully operating outside of an optics laboratory environment due to the extreme vibrational sensitivity of the resulting cavity. Forming an extended cavity by coupling an optical fibre to the laser may be a viable alternative (as described, for example, in [13, 14]).

In summary, considering the requirements of this demonstrator (ie. environmental ruggedness, simplicity, low cost etc.), the advantages of high peak power and smaller pulse durations that are offered by mode-locked semiconductor lasers are probably overridden by the significant disadvantages of higher cost, low availability, increased system complexity and high environmental sensitivity.

3.1.3 The Final Configuration

Thus, from the considerations outlined in Sections 3.1.1 and 3.1.2, it was decided that a 1.3 μm, gain-switched semiconductor laser source would be used in the demonstrator. A laser chip mounted on a chip carrier would be the ideal starting point. The device could then be mounted and have the rf interface optimised for gain-switched operation. Optical fibres could be attached to the output facets using uv-cured expoxy, and the whole system packaged, probably along with the electrical drive electronics.

It was found however that most commercial laser diode suppliers had stopped supplying the laser diodes on chip carriers, due to high breakage rates. A viable alternative was found in a packaged laser diode supplied by BT&D Technologies.

The BT&D Technologies ALS1100-3.0 is an InGaAsP laser diode mounted with no extraneous matching circuitry in a miniature butterfly package. With a lasing wavelength of between 1.28 μm and 1.33 μm depending upon operating temperature, the laser is supplied with a single-mode fibre pigtail for the optical output and a built-in monitoring photodiode to enable simple tracking of laser power or to allow incorporation of a feedback loop to provide laser intensity stabilisation. The cost of the packaged laser was only $1.5 k. A critical unknown factor would of course be the effect of the packaging on the coupling of the fast electrical impulse to the laser diode itself, however with a cw modulation bandwidth specified to be beyond 3 GHz, it was thought that reasonably fast optical response times could be achieved.

The total dimensions of the laser package are 7 mm x 5.5 mm x 4.3 mm. The package was mounted into a channel milled into a brass carrier, with the pins connected to gold microstrip lines fabricated on alumina substrates, as shown in Figure 3.1.

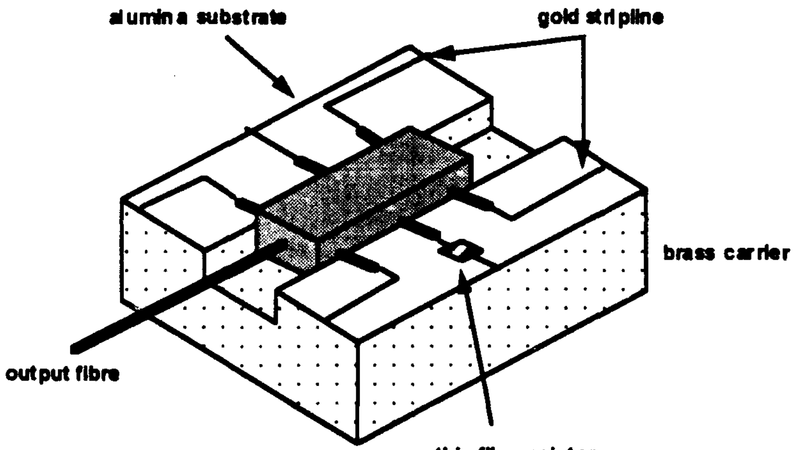

Figure 3.1 Laser diode mount

The differential resistance of the laser was 10 Ω, and so a 40 Ω chromium thin-film resistor was fabricated onto the input line to provide broad-band impedance matching of the device. The carrier was drilled to mount an SMA connector, which was soldered to the input track connecting to the laser cathode via the thin film resistor. All of the thin film fabrication was carried out in-house by DSTO's Micro engineering section.

The entire brass carrier, measuring 22 mm x 19 mm x 18 mm was mounted on an ILX Lightwave LM-4970 laser diode mount with thermoelectric cooler, controlled by an ILX LDC-3722 power supply and temperature controller

Both a fast electrical impulse to drive the laser and the bias current from the LDC-3722 controller were supplied via an HP11612A, 45 MHz - 26.5 GHz bias tee (cost $1.5k). Balancing the impulse power with the dc bias current allowed optical pulse characteristics to be optimised.

3.2 The Electrical Drive Signal

The laser was gain-switched using the impulse response of Hewlett-Packard step recovery diodes (SRD's). The drive signal for the SRD's was supplied by an HP8644A synthesized signal generator, amplified to approximately +27 dBm by a Mini Circuits ZHL-5W-1, 500 MHz bandwidth, 40 dB gain power amplifier. The cost of the amplifier was $2.5 k.

Pulse repetition rates of both 100 MHz and 250 MHz were demonstrated, the only component needing to be changed being the SRD. An HP33002-A SRD was used for the 100 MHz experiments whereas an HP33003-A SRD was used for the 250 MHz experiments. The SRD's cost $0.6 k each.

A 6 dB resistive power splitter was used to split the signal from the signal generator, prior to the power amplifier. One output was connected to the amplifier to drive the SRD, the second output was split a second time and used to both trigger an HP54120A, 18 GHz bandwidth digital sampling oscilloscope and to supply a reference signal for display on the oscilloscope.

The connections for the drive electronics are sho schematically in Figure 3.2 below.

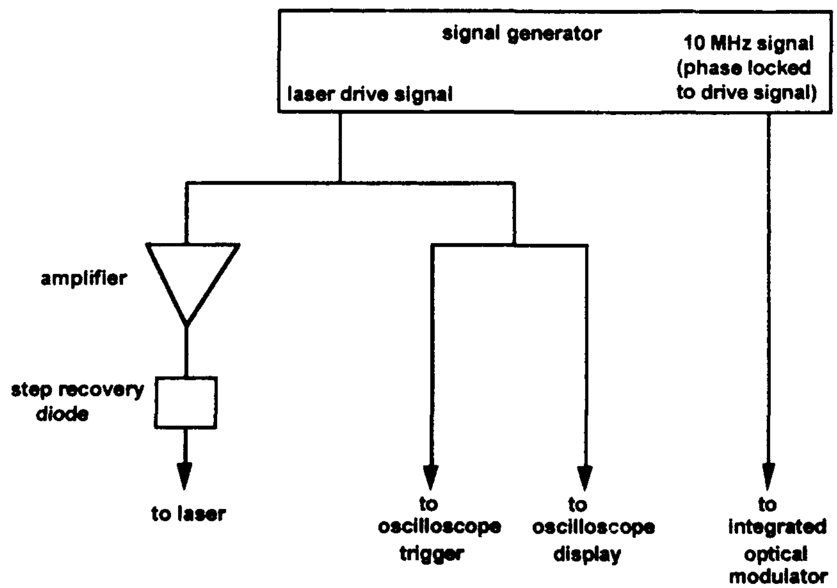

Figure 3.2 Drive electronics schematic

3.3 Integrated Optic Modulator

The optical pulses from the laser diode were coupled via single mode fibre into a New Focus/United Technologies Photonics integrated optical modulator (cost $14 k).

The light from the input fibre is coupled into a waveguide diffused into a lithium niobate ($LiNbO_3$) crystal. The waveguide splits the light equally into two arms, and then combines these arms in order to couple a single waveguide to an output fibre. Thus, the waveguiding structure is essentially a Mach-Zehnder interferometer. The rf signal is applied to one arm of the interferometer, which results in a phase modulation of the light in that arm. The interferometer structure turns this phase modulation into an intensity modulation detectable by a fast photodiode. When properly biased, the intensity varies approximately linearly with rf signal.

The model 4503 modulator used for this experiment is a dual phase and/or amplitude modulator optimised for 1.3 μm laser wavelengths. The rf bandwidth of the amplitude modulator was 4.5 GHz, and the voltage required to switch the modulator from completely on to completely off (a quantity designated as V_{π}) was 12 V.

As shown in Figure 3.2, the signal to be sampled was a 10 MHz signal that was phase-locked to the drive frequency of either 100 MHz or 250 MHz. The reason for using a phase-locked signal was so that the individual optical samples could be resolved when the output from the modulator was detected by a fast photodiode and displayed on an oscilloscope (if the signal was not phase locked, then the optical pulse shapes would wash out underneath the 10 MHz envelope). It should be stressed however that such phase-locking between the sampled signal and the drive signal is not necessary - it is used in this case purely for display purposes.

3.4 Detection

The modulated optical pulses were launched from the output fibre of the modulator and detected by an Electro-Optics PD50 InGaAs photodiode (cost $9 k). The photodiode has an approximately Gaussian impulse response with a full width at half maximum intensity (FWHM) of 50 ps. By approximating the optical pulse as Gaussian, the actual optical pulse duration τ_p can be inferred from the measured pulse duration τ_m as

$$\tau_p \approx \sqrt{\tau_m^2 - 2500}\ ps \tag{3.1}$$

The final launching of the optical power from the end of the modulator output fibre into the detector was the only part of the demonstrator that relied on "free space" coupling, simply because the only available detector, the PD50, did not have a fibre pigtail. Ideally, a fibre pigtailed detector such as the 20 GHz bandwidth BT&D PDC4310-30 detector (cost $6 k) would be fusion spliced to the output fibre of the modulator, thus completing a fully guided-wave system.

The electrical output of the photodiode was displayed either on the 18 GHz bandwidth HP54120A sampling oscilloscope (in the case of characterising the FWHM of the optical pulse), or on a Tektronix 620 sampling oscilloscope (in the case of displaying the sampled 10 MHz envelope).

The necessity of using the lower bandwidth Tektronix oscilloscope arose due to a combination of timebase drift and undersampling which is associated with trying to display very rapid events (tens of picoseconds FWHM) on a total display width of several hundreds of nanoseconds (two cycles of 10 MHz signal) with a finite number of display points (500 in the case of the HP54120A). The accuracy of the timebase scan is only accurate to a certain percentage of the total timebase. When combined with the finite resolution of the sampling oscilloscope, this essentially led to undersampling of the individual optical pulses and strong aliasing of the signal such that a psuedo-replica of an "average" picosecond pulse ends up expanded across the entire display. This problem was somewhat artificially circumvented in the Tektronix TDS620 oscilloscope since the pulse duration is artificially increased due to the lower response time of the oscilloscope and the ability of the TDS620 to display more points. At sufficiently large timebases however, the TDS620 could also be made to exhibit the aliasing problem.

4 RESULTS

In this section the testing and characterisation of the individual components is described and the overall performance of the system is presented.

4.1 The Electrical Drive Signal

The first stage of the task was to characterise the response of the SRD's. The test set-up is shown in Figure 4.1.

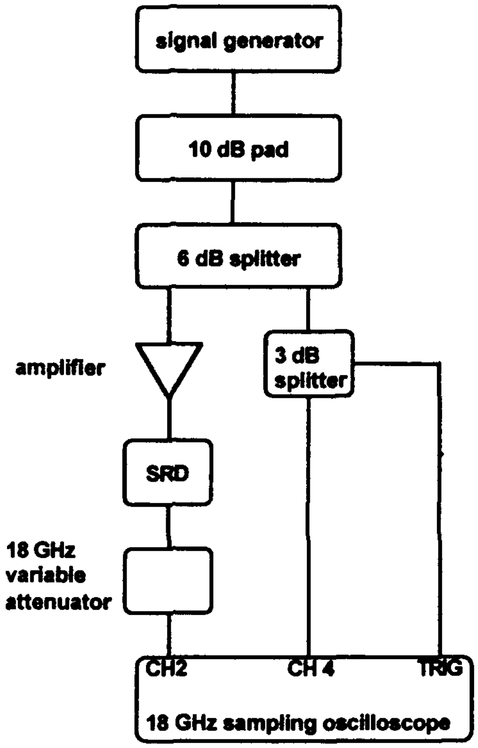

Figure 4.1 SRD characterisation set-up

The gain of the amplifier was measured to be 46 dB at 100 MHz. The specified maximum input power into the SRD's is +30 dBm, and so with the arrangement shown above an output power of up to 0 dBm can be tolerated from the signal generator. This also results in trigger and monitor channel (channel 4) power levels of -19 dBm, which are well within the safe operating range of the sampling oscilloscope.

Figure 4.2 shows the measured response of the SRD at 100 MHz, using 128 sample averaging. It is apparent that the pulses have a slight ringing characteristic on the trailing edge, with the entire transient appearing on top of a portion of the input 100 MHz tone - a phenomenon known as "feed through".

Figure 4.3 is an expanded view of an individual electrical pulse. The measured FWHM of the pulse is 140 ps.

Figures 4.4 and 4.5 show the frequency content of the electrical pulse. It is apparent that significant frequency content extends well out over ten gigahertz.

Figures 4.6 and 4.7 show the output impulses from the 250 MHz SRD. It is clear that the feed-through problem is worse for these devices, although the ringing characteristic on the trailing edge is similar in proportion to the impulse peak. The measured FWHM for these pulses is 80 ps.

The peak signal amplitudes from the SRD's were in excess of 7 V. For both SRD's it was found that the electrical pulse FWHM narrowed with increasing power from the signal generator.

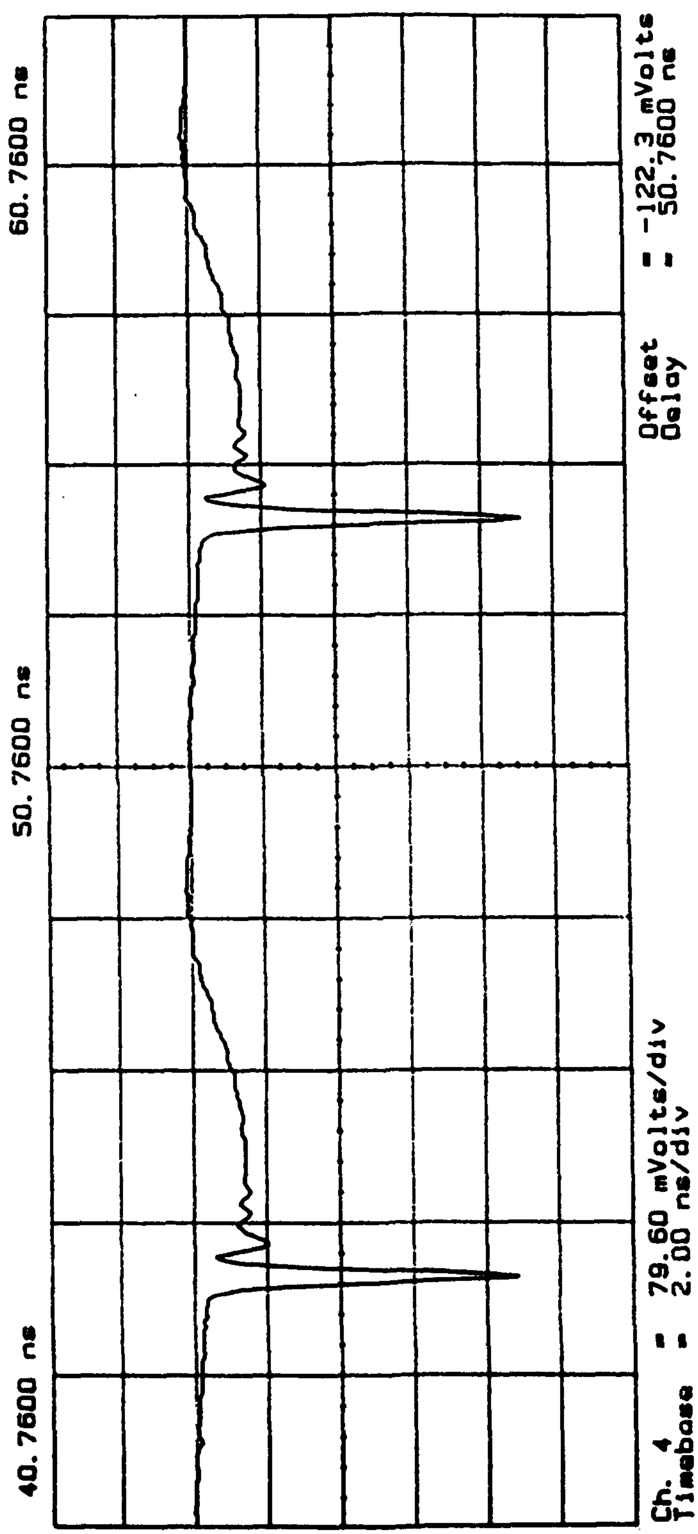

Figure 4.2 Response of step recovery diode - electrical pulse train at 100 MHz

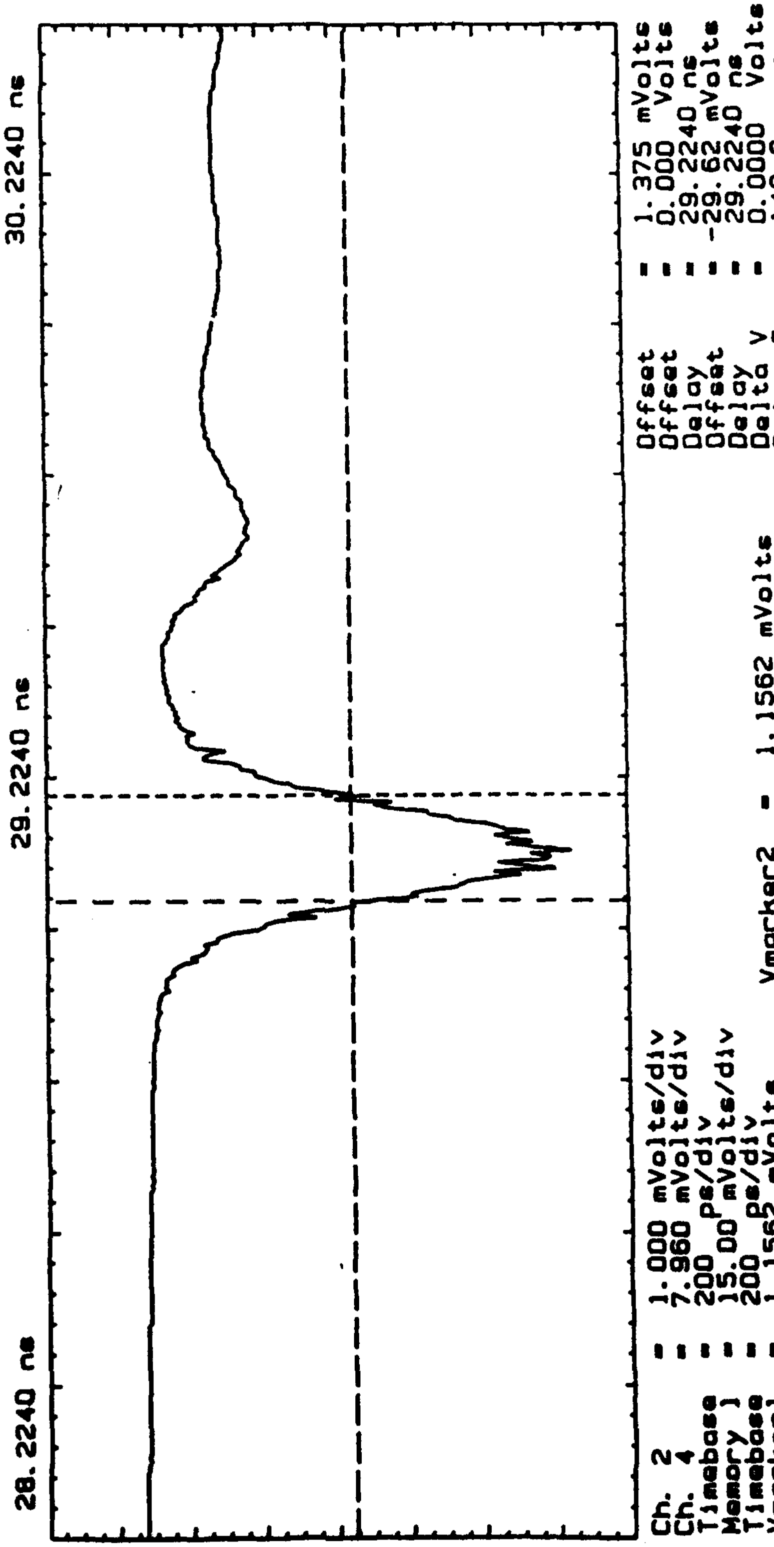

Figure 4.3 Expanded view of electrical drive pulse (100 MHz).

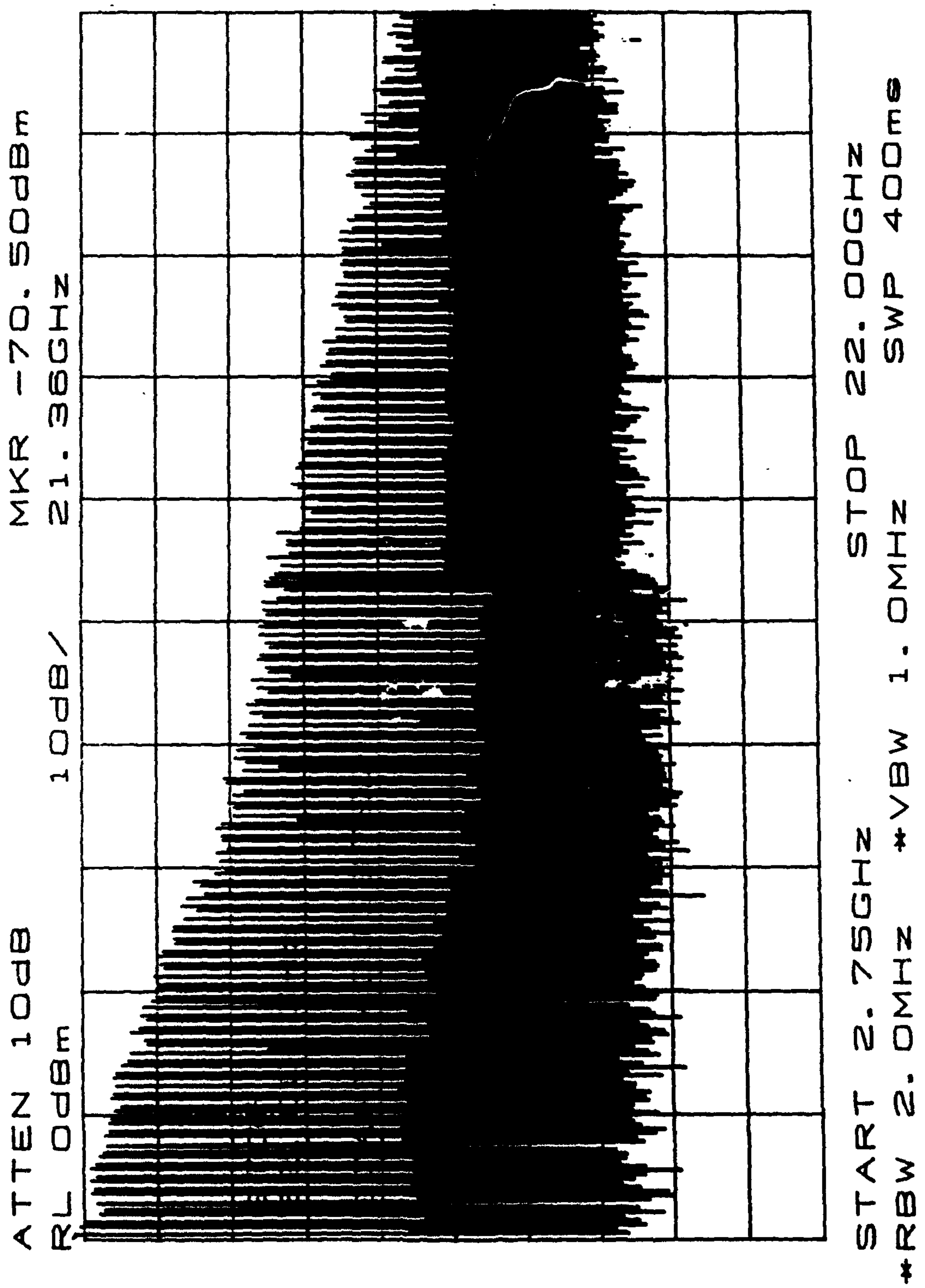

Figure 4.4 Spectrum of 100 MHz electrical pulse train.

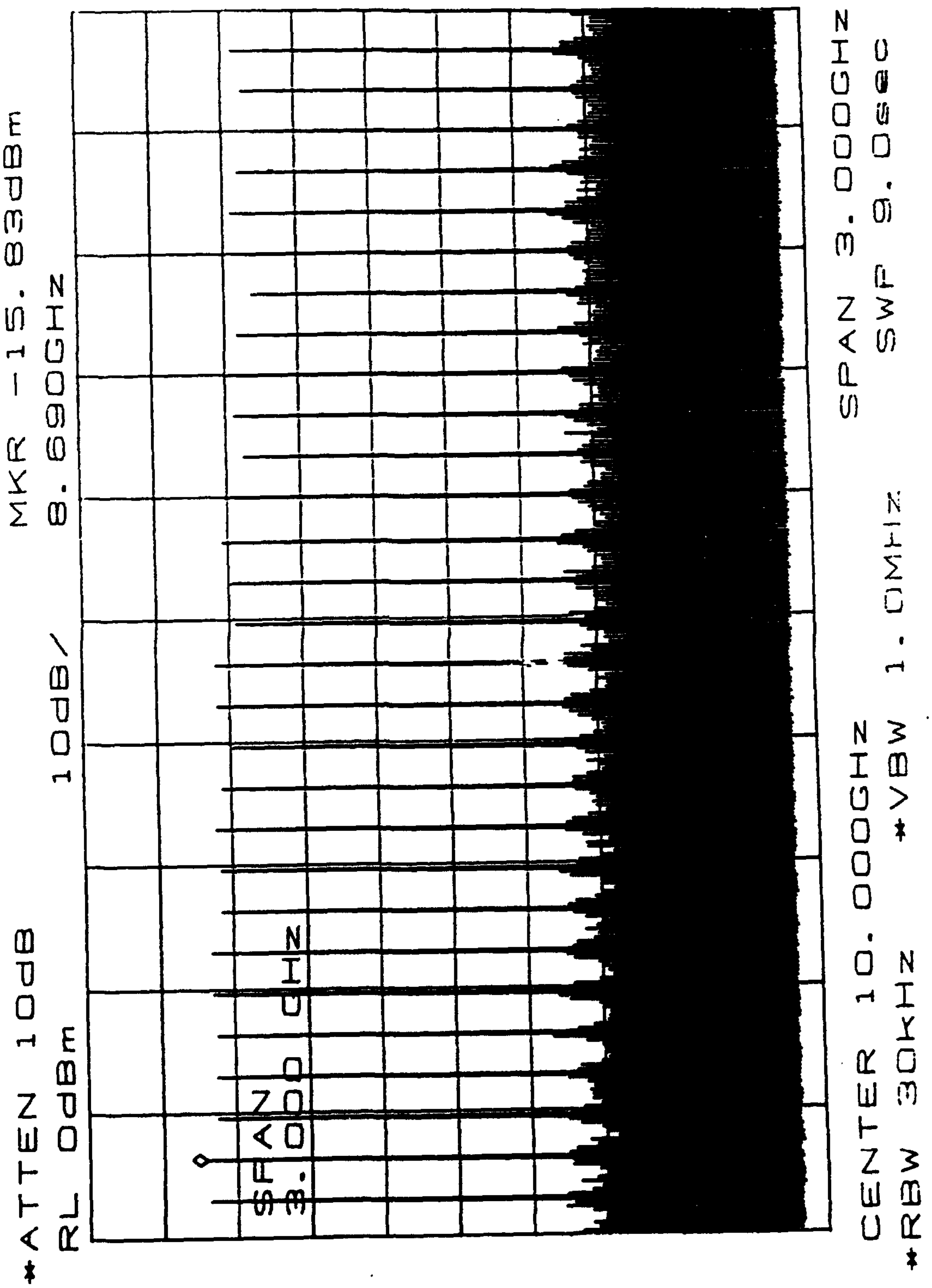

Figure 4.5 Expanded view of spectrum around 10 GHz.

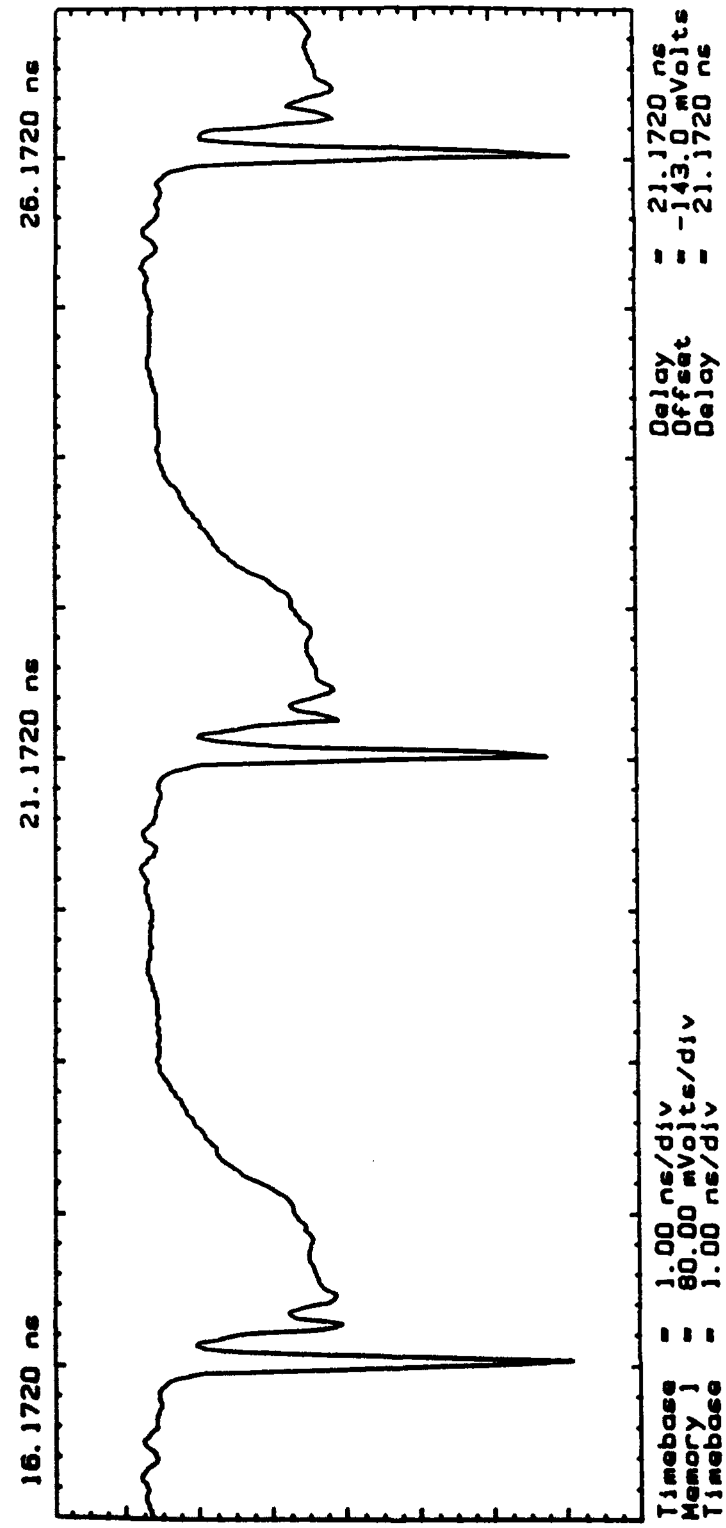

Figure 4.6 Response of step recovery diode - electrical pulse train at 250 MHz.

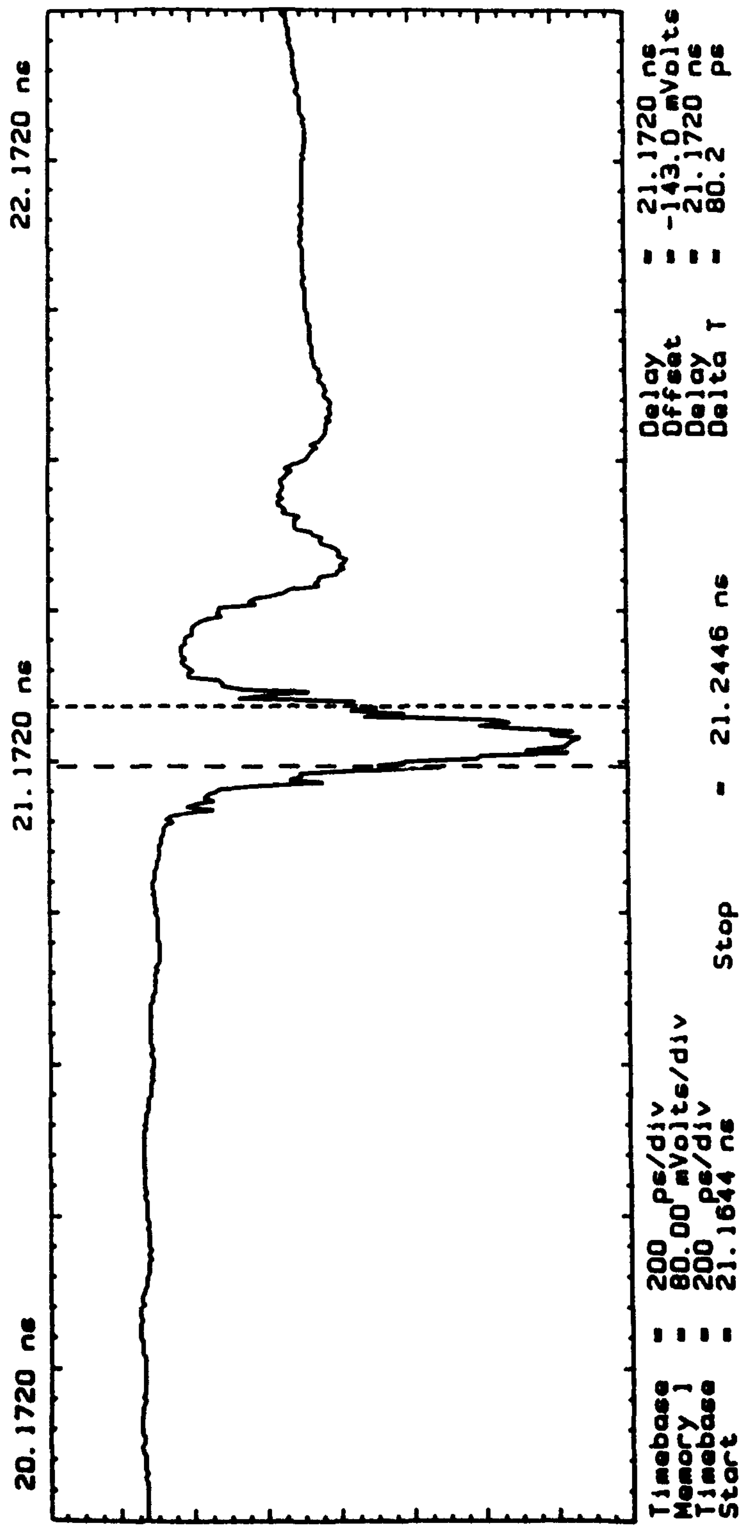

Figure 4.7 Expanded view of electrical drive pulse (250 MHz).

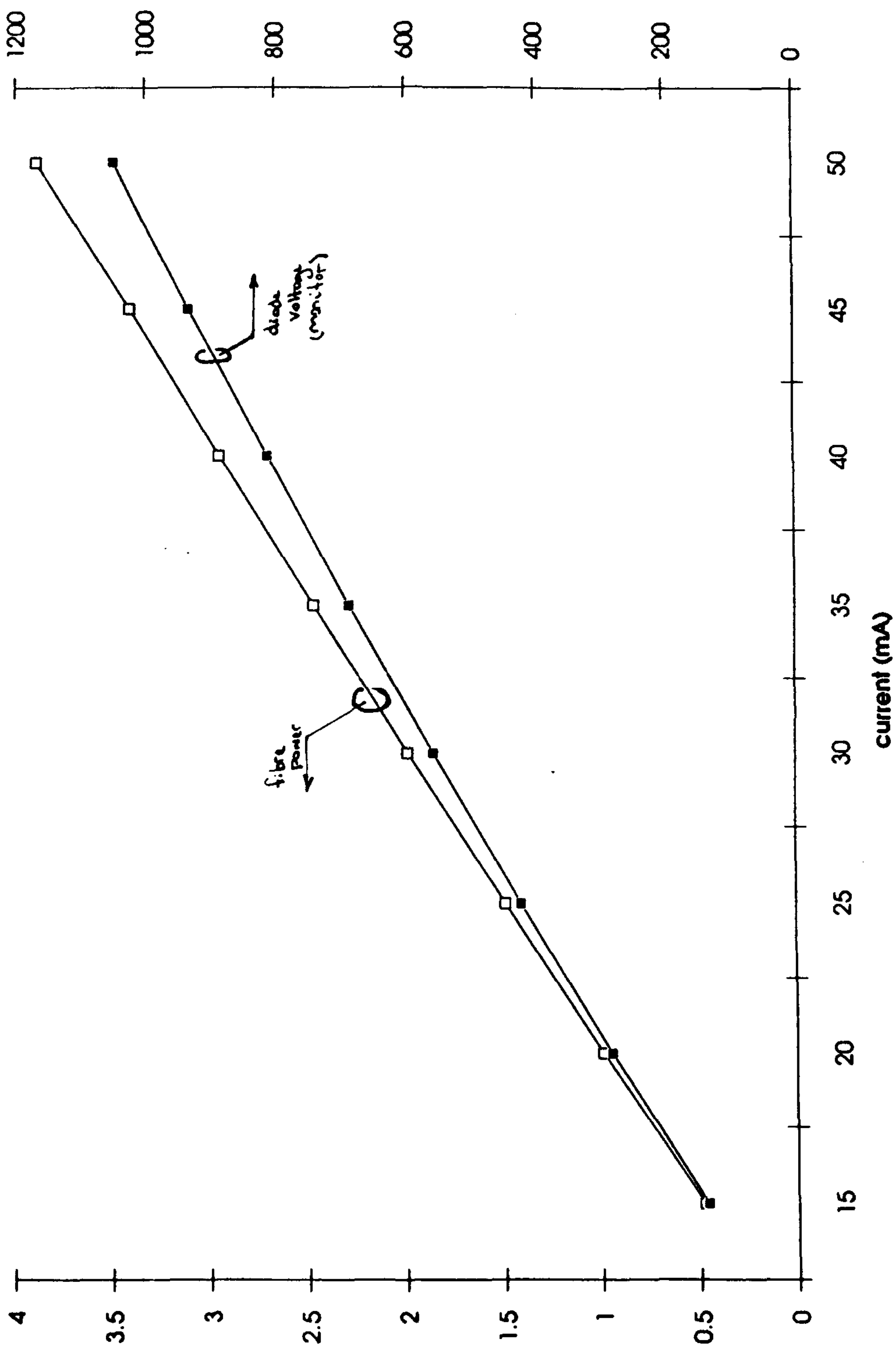

Figure 4.8 Characterisation of laser diode response.

4.2 Characterising the Laser Diode

Prior to attempting to gain switch the laser diode, the cw characteristics of the laser and the microwave modulation characteristics of the laser plus mounting package were determined. The optical power output from the fibre pigtail of the laser was measured using a Coherent Fieldmaster power meter. This measurement was used to calibrate the signal from the monitor photodiode by measuring the voltage drop of the photodiode current across a 1 k resistor. This measurement then enabled the fibre-coupled optical power to be determined simply by measuring the voltage drop across the resistor.

The results of the measurements are shown in Figure 4.8. The relationship between monitor voltage and fibre coupled optical power was found to be

$$P(mW) = (3.74 \pm 0.07)V - (0.07 \pm 0.05) \tag{4.1}$$

The threshold current of the laser was determined to be ~10 mA.

The next characteristic to determine was the microwave response of the laser and mount. The experimental arrangement for the measurement is shown in Figure 4.9.

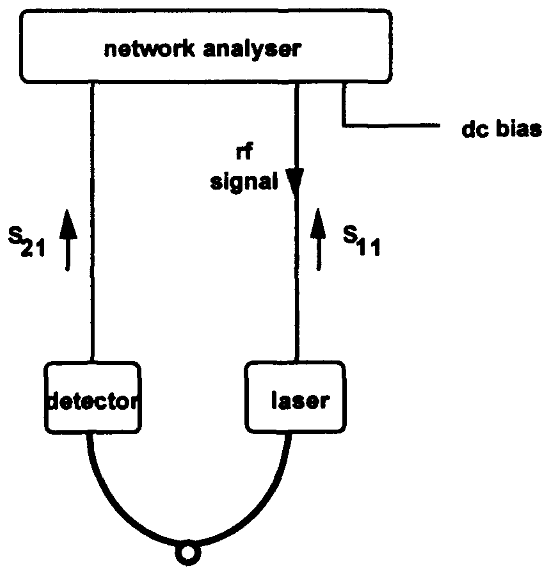

Figure 4.9 Measuring the microwave characteristics

The dc bias to the laser diode was applied via a pre-calibrated bias tee built into the network analyser. The detector was the PD50 fast photodiode. Figure 4.10 shows the measured S11 and S_{21} parameters from 40 MHz to 12 GHz.

WILTRON

360 NETWORK ANALYZER

MODEL:	DATE:	
DEVICE:	OPERATOR:	
START: 0.0400 GHz	GATE START:	ERROR CORR: 12 - TERM
STOP: 12.0000 GHz	GATE STOP:	AVERAGING: 1 PTS
STEP: 0.0720 GHz	GATE:	IF BNDWDTH: REDUCED
	WINDOW:	

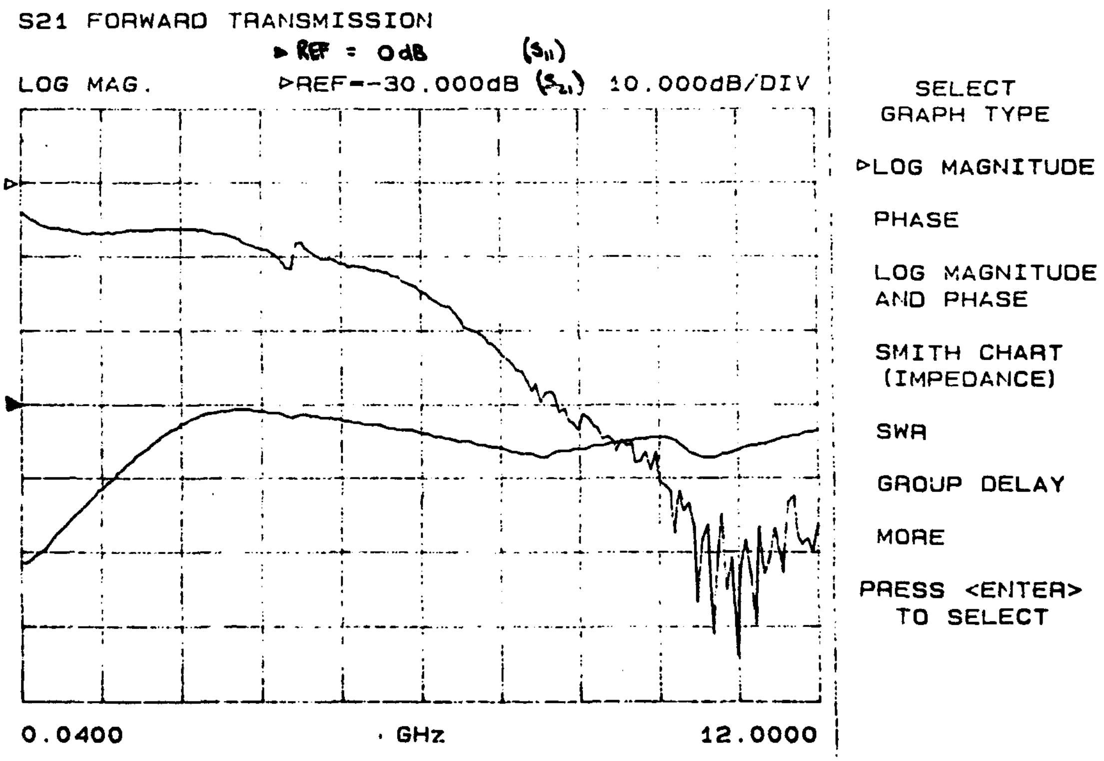

Figure 4.10 Measured S_{11} and S_{21} parameters for the directly modulated laser diode.

The insertion loss of this rudimentary microwave link is about 35 dB (comparable in fact to commercially available microwave fibre optic links). The response is reasonably flat out to ~3 GHz, dropping to -3 dBc at ~4.8 GHz. The S_{11} reflection coefficient rapidly approaches 0 dB at about 3 GHz, indicating that the input matching has become extremely poor, and that a substantial amount of the input microwave power is being reflected back into the signal port of the spectrum analyser. However, it appears that usable amounts of microwave power up to about the 3 GHz region is coupling into the laser. This is consistent with the frequency of operation specified by the manufacturers, and as such it was decided that the microwave characteristics of the optical source were adequate for the experiment.

4.3 Gain Switched Operation of the Laser Diode

Having established suitable operation of the SRD's and the laser diode, the electrical impulses from the SRD were used to gain switch the laser source. The experimental arrangement to characterise the optical pulses from the gain switched laser is shown in Figure 4.11.

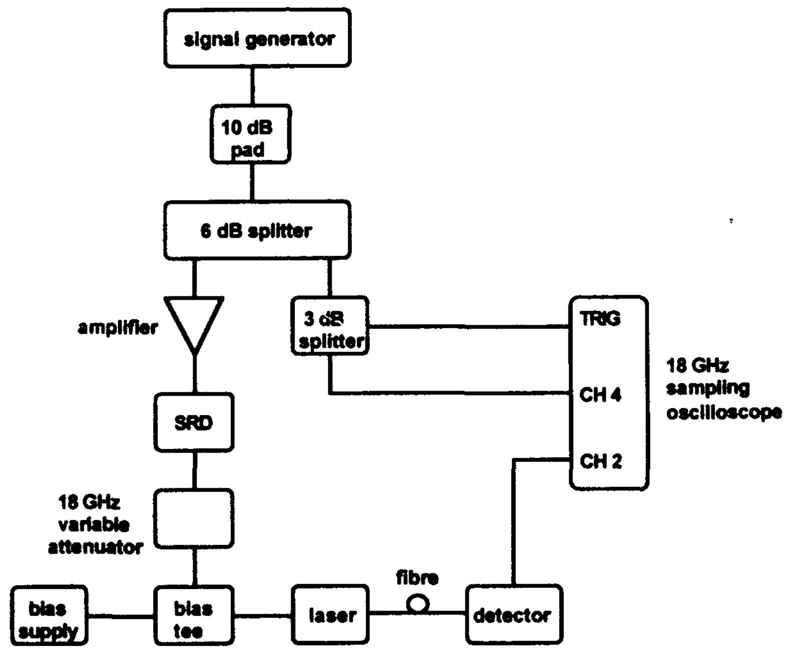

Figure 4.11 Experimental arrangement to determine gain switching parameters

The bias supply and impulse amplitude into the bias tee were varied in order to determine operating conditions required to obtain the best gain-switched optical pulse. It was found that the best pulses occurred under the following ranges of parameters:

power from signal generator	:	-6 dBm → -4 dBm
attenuation in SRD	:	-1 dB → 0 dB
bias current	:	5 mA → 7 mA

These results indicated that the attenuator was not really necessary, since the improvements in the electrical impulse characteristics with increasing rf power were negligible. The optical pulses obtained at 100 MHz and 250 MHz repetition rates are shown in Figures 4.12 and 4.13 respectively.

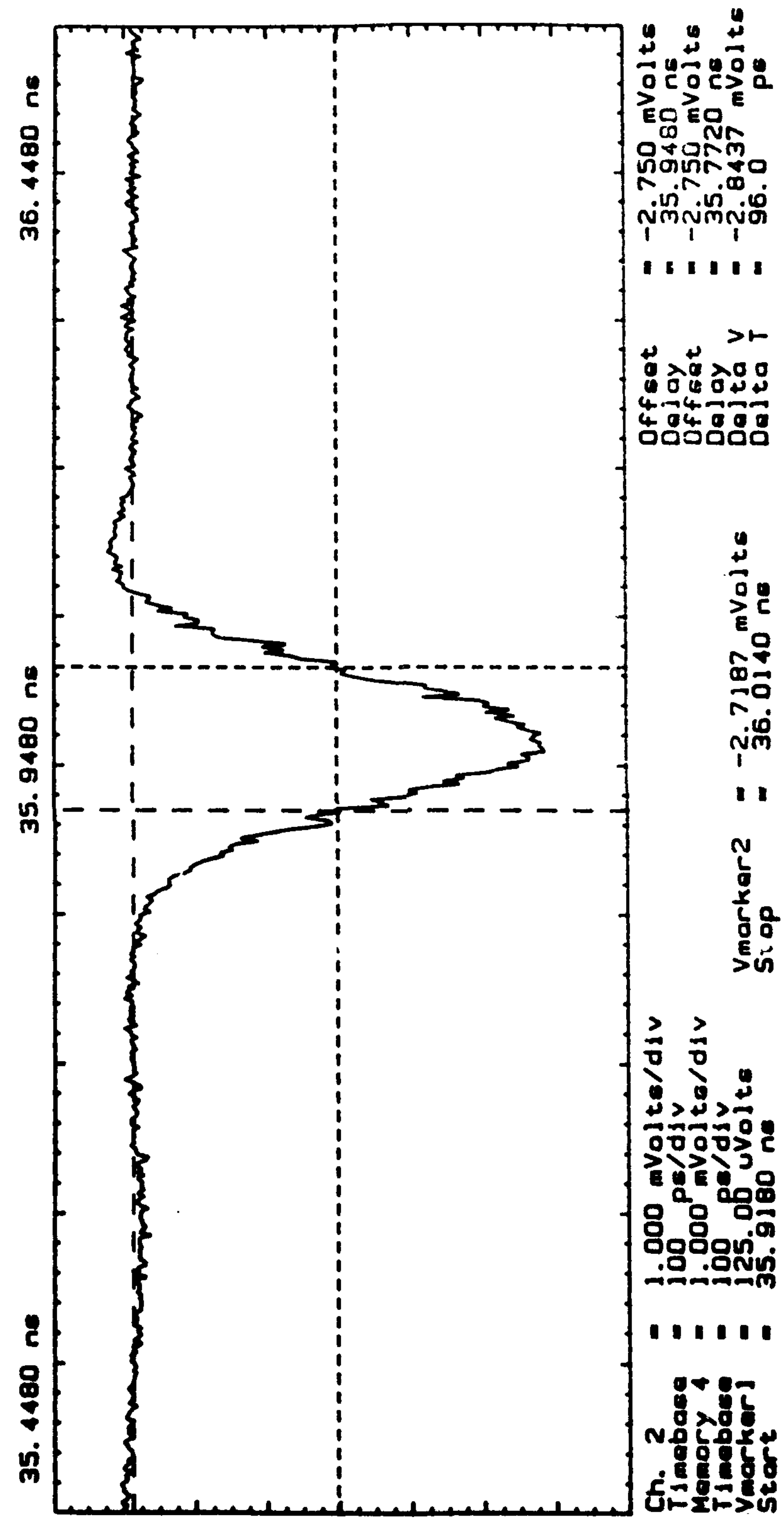

Figure 4.12 Measurement of optical pulse FWHM (100 MHz repetition rate).

The measured FWHM of the optical pulses at a repetition rate of 100 MHz was found to be ~95 ps. From equation (3.1) this implies an actual pulse duration of ~80 ps FWHM. At a repetition rate of 250 MHz, the FWHM of the optical pulse was measured to be ~90 ps, corresponding to an actual FWHM of ~75 ps. Thus, at both repetition rates, the estimated FWHM of the optical pulses was found to be of the order of 75 - 80 ps. When compared to the measured duration of the electrical drive pulses (140 ps at 100 MHz and 80 ps at 250 MHz), it would appear that the packaging of the device and/or the gain-switching dynamics of the laser are limiting the attainable optical pulse durations.

When the bias current was set too high, or the rf power was increased past the optimum point for a given bias current, it was possible to produce well-structured, groups of pulses with 2, 3, 4 or more optical pulses for each electrical drive impulse. An example of a 4-pulse group is shown in Figure 4.14. Preliminary measurements on 2, 3 and 5-pulse groups indicated that the time between the pulses is roughly (430 ± 30) ps. This is consistent with the pulse separations shown in Figure 4.14. The origin of the pulse group is ascribed to reflections associated with impedance mismatches in the electrical transmission lines, probably at the transitions from the SMA connector to the microstrip and the microstrip to the laser package. The problem can be minimised by using more care to mount the laser.

An interesting feature of the pulse group i that the optical pulse amplitudes do not exponentially decay as might be expected if they resulted purely from multiple electrical reflections of the drive pulse. As can be seen, the amplitudes of the first, third and fourth pulses are approximately equal, whereas the second pulse is largest. This interesting feature may indicate that gain relaxation dynamics within the semiconductor structure are playing a significant role in the detail of the pulse formation process at timescales well beyond that of an individual pulse FWHM. Such detail should be able to be modelled via a rate equation approach to gain-switched laser dynamics.

Figure 4.15 shows the optical pulses from the 100 MHz SRD and the sinusoidal drive signal to which they are locked. Figure 4.16 shows the optical pulse train at 250 MHz.

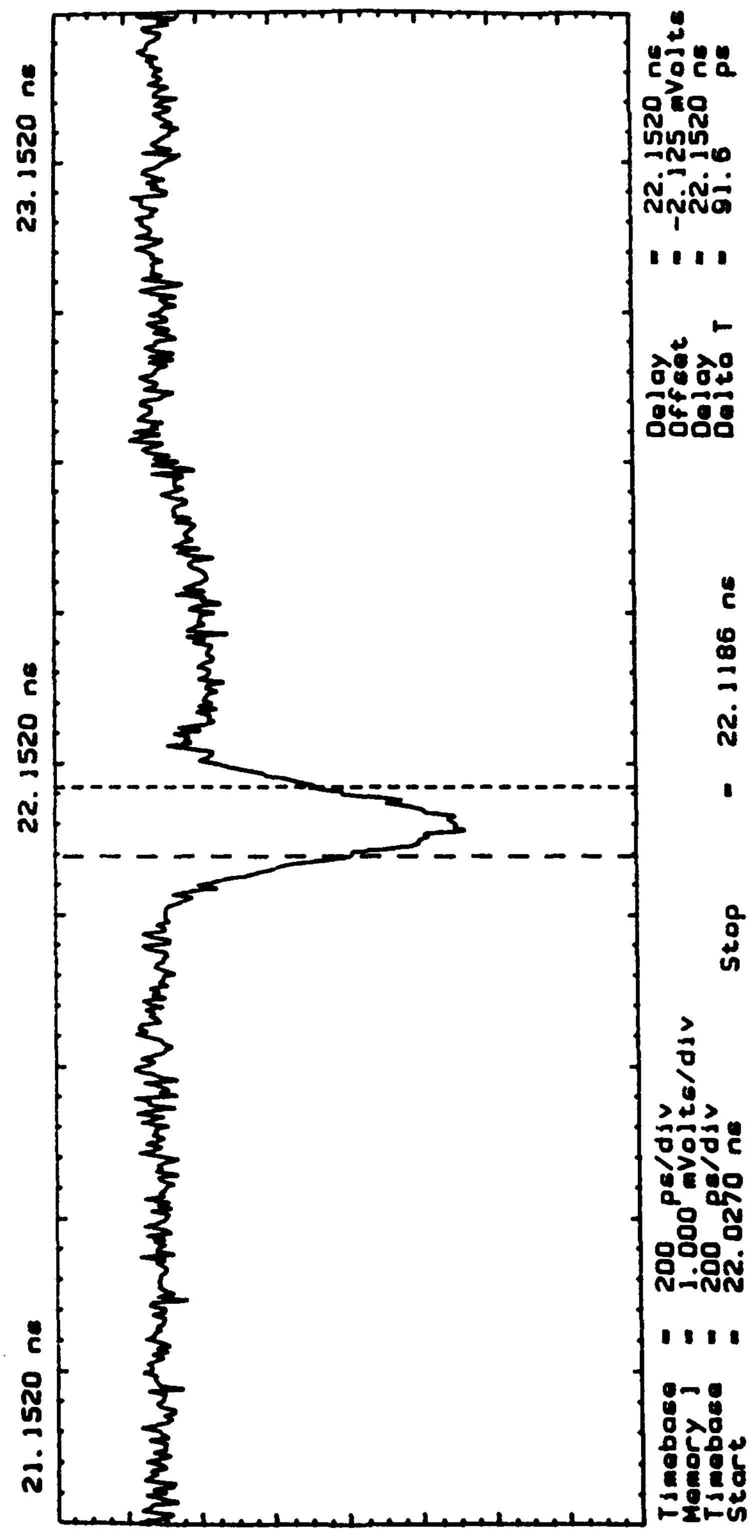

Figure 4.13 Measurement of optical pulse FWHM (250 MHz repetition rate).

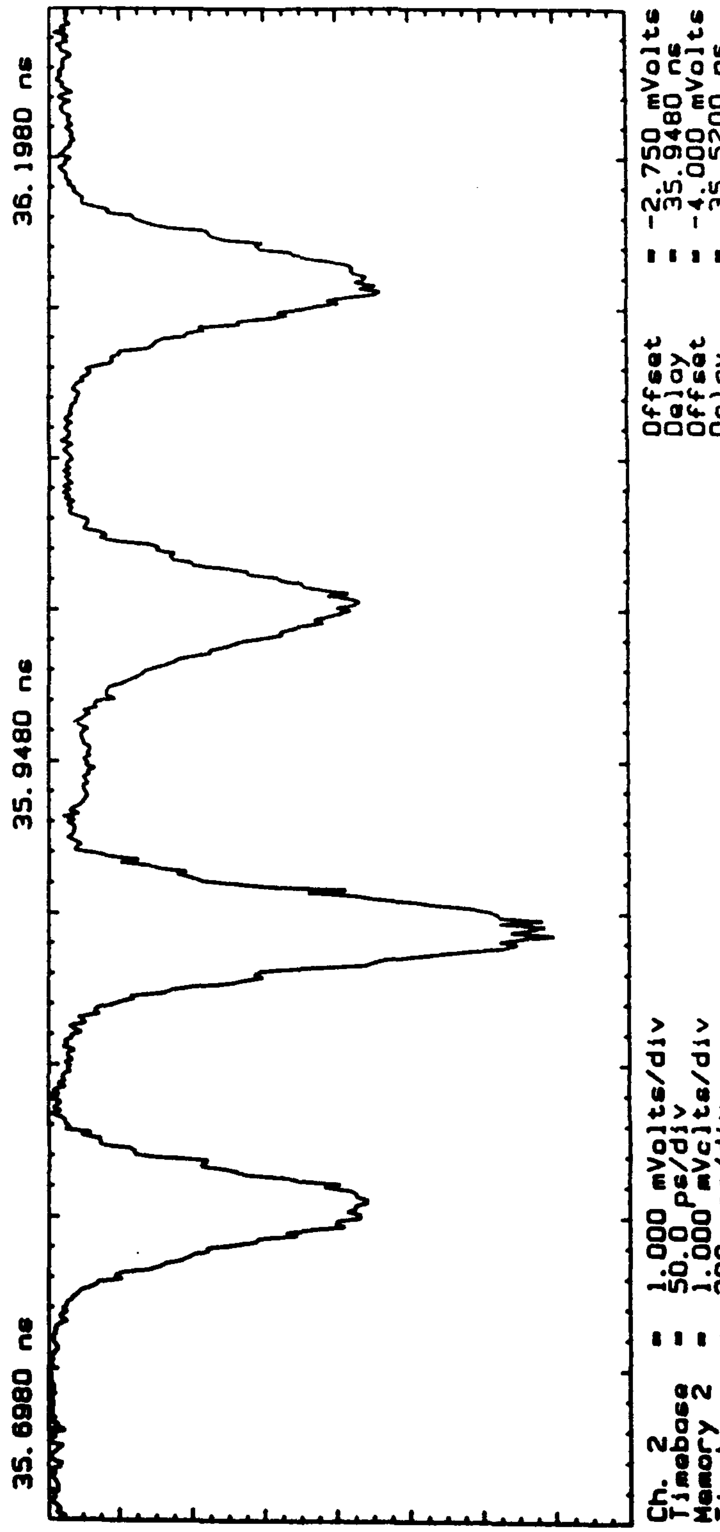

Figure 4.14 Example of multiple pulse formation at higher drive powers.

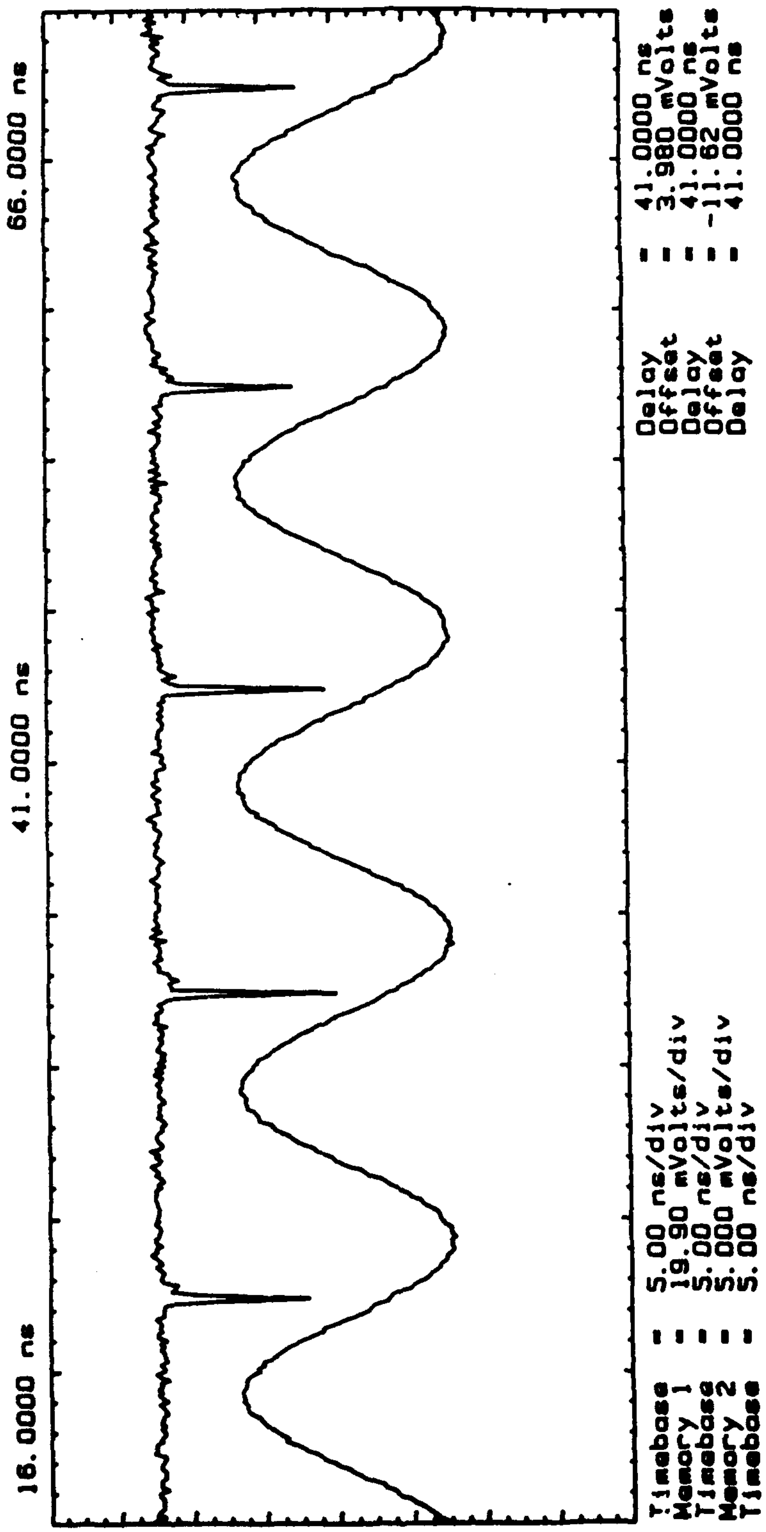

Figure 4.15 100 MHz optical pulse train and drive signal.

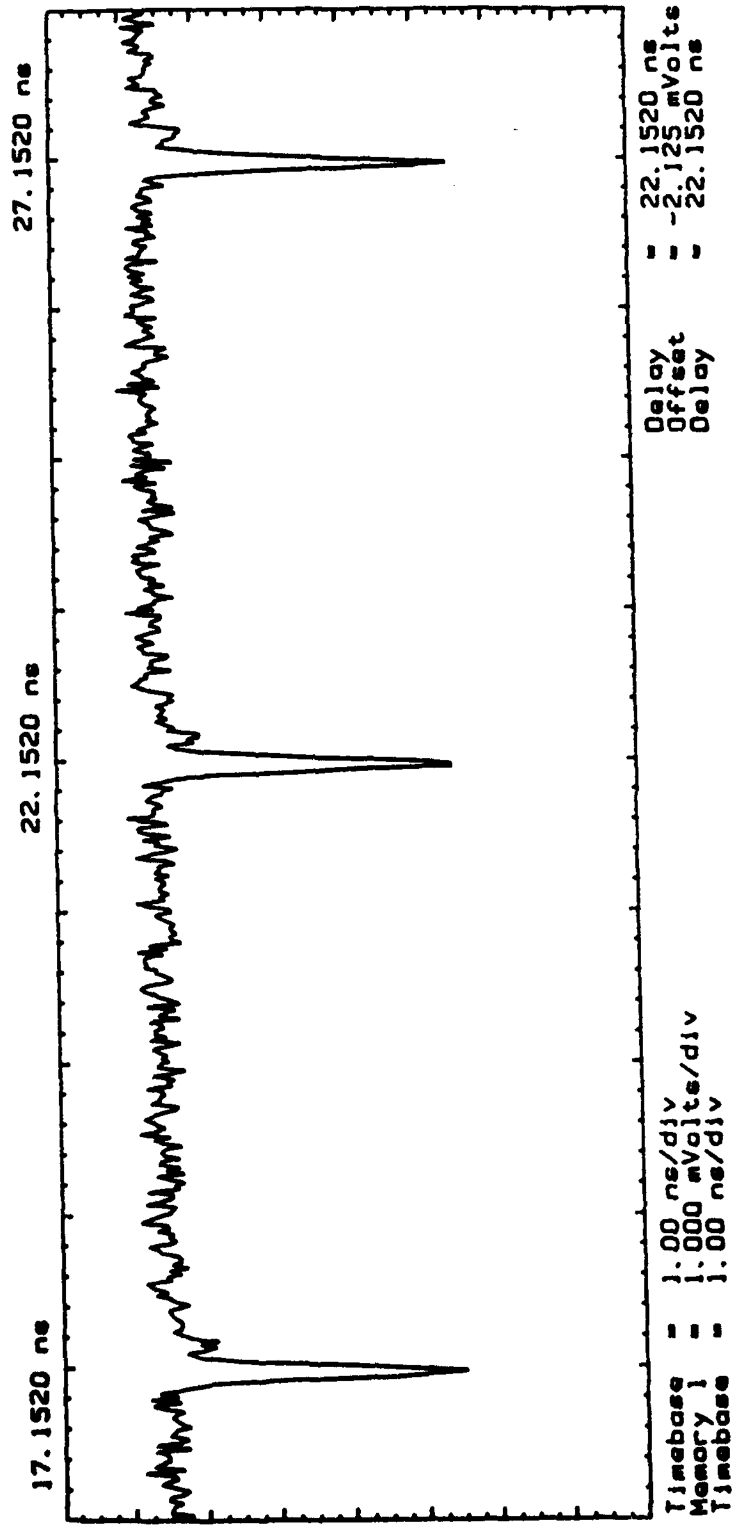

Figure 4.16 250 MHz optical pulse train.

4.4 The Integrated-Optic Sampler

The output fibre from the laser diode was fusion spliced to the polarisation-preserving input fibre of the modulator. The quality of the fusion splice was quite poor, resulting in an overall optical insertion loss of the sampler of ~12 dB (the intrinsic optical insertion loss of the modulator was quoted as 6 dB). The mis-alignment between the fibre cores could be clearly seen under a microscope. It was decided to attempt the experiment despite the large optical loss, since (i) the fusion splicer was not designed for polarisation-preserving fibre, and no guarantee could be made on the improved quality of further attempts, and (ii) in the case of the fibre from the laser, it proved to be quite difficult to strip enough of the outer jacket to comfortably splice the fibres without breaking the fibre altogether. As such it was decided to press on and attempt the experiment, going back to improve the splice only if it was found that the amount of optical power was inadequate to demonstrate the system. In the meantime a jig was constructed to ensure that the outer jacket of the fibre from the laser could be stripped without damaging the delicate inner core. Since completing the experiment the simple jig has been implemented and after some experience, stripping and fusion splicing of normal fibre to the polarisation preserving fibre from the laser can be routinely achieved with estimated excess losses of less than 0.05 dB as estimated by the fusion splicer. The actual loss is probably closer to 1 dB or so.

As outlined in Section 3.3 the signal to be sampled was chosen as the 10 MHz signal provided at the rear panel of the signal generator, to which the pulse repetition rate of the laser was phase-locked. This allowed the optical sampling pulses to be resolved beneath the modulation signal. It is stressed again that such phase-locking is *not* a necessary part of the system, the 10 MHz being chosen for demonstration purposes only.

Figure 4.17 shows the result of optically sampling the 10 MHz test signal at a rate of 100 MHz. Figure 4.18 is an expanded view of the same signal. The optical pulse durations are artificially broadened due to the limited response time of the 2 GHz Tektronix 620 sampling oscilloscope used to record the data. The 10 MHz modulation on the negative-going optical pulses is apparent. The slight asymmetry of the modulation response is due to the fact that the modulator was not biased exactly to optimal linearity (the modulator bias was essentially set by estimating by eye the symmetry of the oscilloscope trace).

Figure 4.19 shows the result of sampling the 10 MHz signal at a rate of 250 MHz. The same comments regarding apparent optical pulse duration and modulation asymmetry apply as for Figure 4.17.

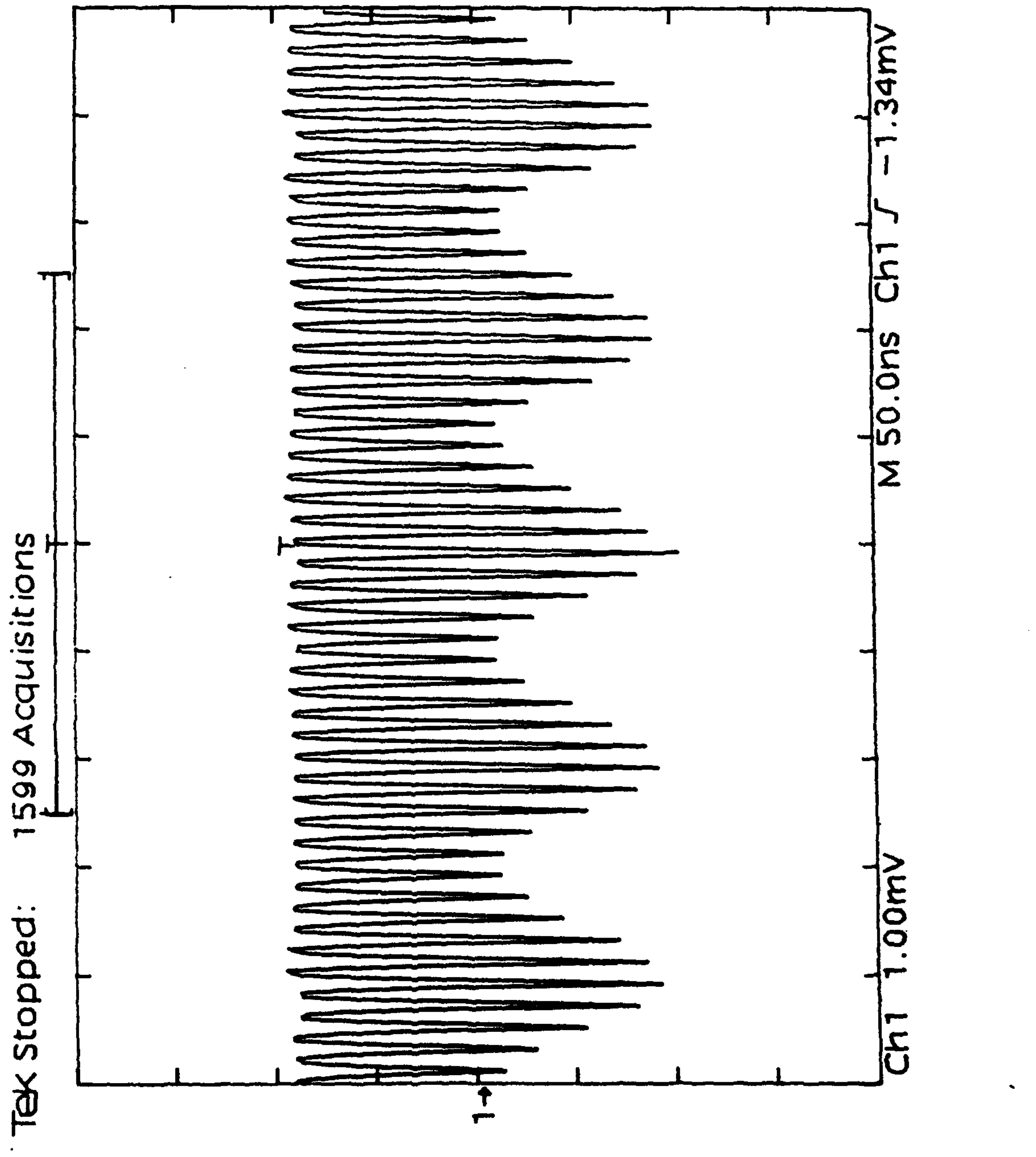

Figure 4.17 Sampling a 10 MHz sinusoid test tone at 100 MHz. The 10 MHz tone appears as an amplitude modulation on the negative-going optical pulse signal.

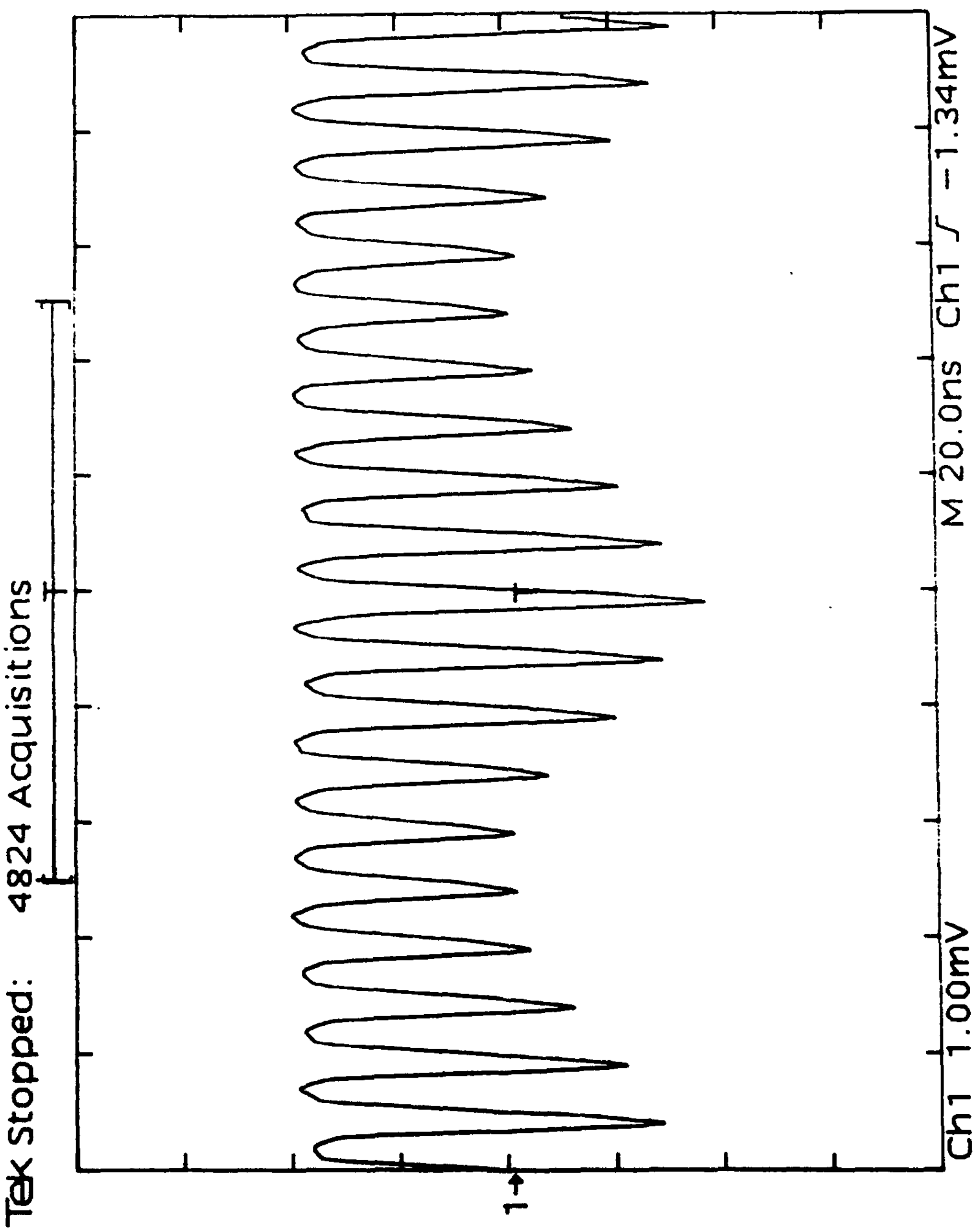

Figure 4.18 Expanded view of the sampling of the test tone. This measurement clearly shows the artificial broadening of the optical pulse FWHM from 75 ps to ~400 ps.

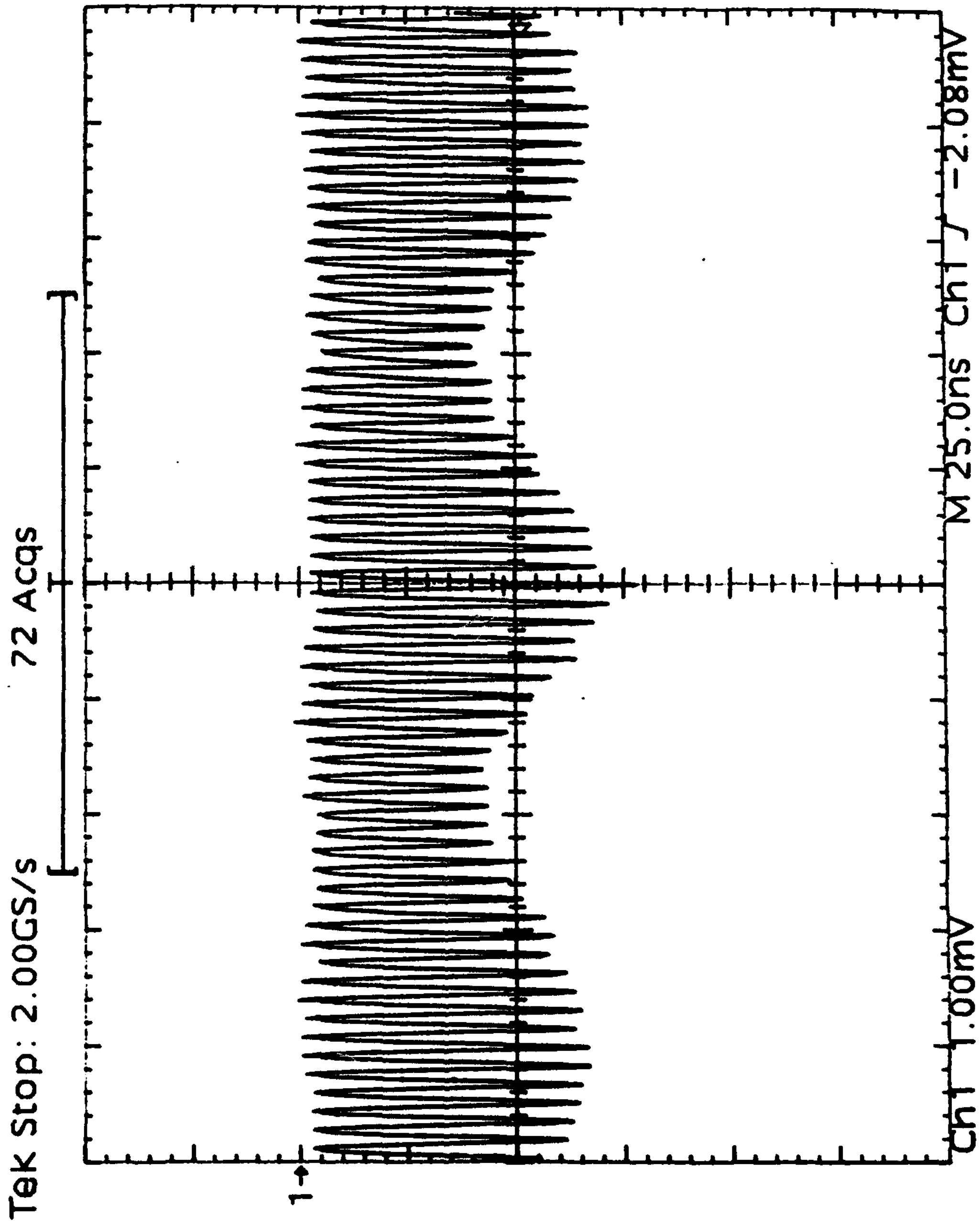

Figure 4.19 Sampling the 10 MHz test tone at 250 MHz.

4.5 Improvements to the Current System

The performance of the current system can be enhanced substantially. The total optical insertion loss of the system can be reduced by optimising the polarisation state into the modulator by including a fibre-loop polarisation controller, and re-splicing the fibre connection to the modulator. Every 1 dB of improvement in optical insertion loss results in 2 dB of electrical improvement in the total system.

The sampling rate can probably be extended to ~8 GHz by using a 1 GHz SRD to gain-switch the laser, followed by a fibre optic multiplexing system to split the pulse train, delay one of the pulse trains by half the sampling period and recombining again. This can be readily achieved using cheap 3 dB couplers. Improved microwave mounting of the laser should reduce spurious reflections and allow higher rf drive powers without multiple pulsing, thereby increasing the optical power in each pulse. Finally, there is the question of the effect of reflections from poor splices coupling back into the laser and the possibility of causing optical instability. This problem is easily avoided by inserting an optical isolator into the fibre optic line.

5 CONCLUSIONS

In summary, a simple photonic-based RF sampling demonstrator has been constructed in which sampling at rates of up to 250 MHz have been demonstrated. The sample acquisition time is about 75 ps. The total cost of implementing the optical system, excluding the drive electronics, was less than $25k, with over half this cost associated with the 4.5 GHz bandwidth integrated optical modulator. The cost of the 75 ps laser source itself was of the order of $5k. Electronic Warfare Division currently has a University research project underway to build integrated optical modulators in-country. Modulators already constructed under this contract have bandwidth performances well in excess of the 250 MHz capability of the sampler. Use of these modulators would reduce the total cost of the current system to ~$9k.

The main aims of the project - to demonstrate an inexpensive, rugged optical sampling system that exhibited picosecond aperture times and could readily cover the HF spectrum to 100 MHz - have been realised. There is substantial room for improved performance with the current demonstrator, particularly in the areas of microwave matching and reducing optical loss of the system.

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19. Abstract

A compact, rugged and inexpensive optical sampling system has been constructed. The aperture time of the sampler is estimated to be 75 ps, and sampling rates of 100 MHz and 250 MHz have been demonstrated. The performance of the demonstrator can be enhanced to gigahertz sampling rates without a substantial increase in cost.